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EVALUATION OF MAGNETIC INSULATION IN SF₆ FILLED REGIONS*

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Abstract

The use of magnetic fields perpendicular to quasi-static electric fields to deter electrical breakdown in vacuum, referred to as magnetic insulation, is well understood and used in numerous applications. Here we define quasi-static as applied high-voltage pulse widths much longer than the transit time of light across the electrode gap. For this report we extend the concept of magnetic insulation to include the inhibition of electrical breakdown in gases. Ionization and electrical breakdown of gases in crossed electric and magnetic fields is only a moderately explored research area. For sufficiently large magnetic fields an electron does not gain sufficient energy over a single cyclodial path to ionize the gas molecules. However, it may be possible for the electron to gain sufficient energy for ionization over a number of collisions. To study breakdown in a gas, the collective behavior of an avalanche of electrons in the formation of a streamer in the gas is required. Effective reduced electric field (EREF) theory, which considers the bulk properties of an electron avalanche, has been successful at describing the influence of a crossed magnetic field on the electric field required for breakdown in gases; however, available data to verify the theory has been limited to low gas pressures and weak electronegative gases. High power devices, for example explosively driven magnetic flux compressors, operate at electrical field stresses, magnetic fields, and insulating gas pressures nearly two orders of magnitude greater than published research for crossed fields in gases. The primary limitation of conducting experiments at higher pressures, e.g. atmospheric, is generating the large magnetic fields, 10's Tesla, and electric fields, >100 kV/cm, required to see a significant effect. In this paper we describe measurements made with a coaxial geometry diode, form factor of 1.2, operating at peak electrical field stress of 220 kV/cm, maximum magnetic field of 20 Tesla, and SF₆ pressure of 760 torr.

I. INTRODUCTION

The goal of this work was to extend the measured performance of SF₆ as an electrically insulating gas in crossed fields to 760 torr and demonstrate magnetic insulation in a dense gas. Our measurements can be used

to determine appropriate scaling at higher pressures and fields.

In quasi-static pulsed power systems, a crossed magnetic field deflects electrons into a cyclodial path between collisions with gas molecules. Although an electron may not gain sufficient energy over a single cyclodial path in a high magnetic field to ionize the molecule, it may be possible over a number of collisions for the electron to gain the necessary energy for ionization. It is the collective behavior of an avalanche of electrons in the formation of a streamer in the gas that leads to breakdown. Blevin and Haydon [1] derived the concept of equivalent pressure to describe the effect of the magnetic field on the collective electron properties such as the energy distribution, mean energy, and drift velocity. The equivalent pressure can be expressed as

$$p_e = p \left[1 + \left(\frac{eL}{mu} \right)^2 \left(\frac{B}{p} \right)^2 \right]^{\frac{1}{2}}, \text{ where} \quad (1)$$

p is the pressure, B is the magnetic induction, L is the mean free path at 1 torr, u is the average electron velocity. Intuitively it is reasonable that the collective behavior under the influence of the magnetic field would be similar to an increase in gas pressure since the deflected electron orbits would lead to more collisions per unit distance in the direction of the electric field. Gas number density has replaced pressure in gas discharge literature and the equivalent pressure concept is referred to as the equivalent increased density concept (EIDC) [2].

Blevin and Haydon assumed that the energy distribution of electrons is Maxwellian, the magnetic field does not alter the form of the distribution, and v , the effective electron-molecule collision frequency, is constant. Heylen [3] proved a less restrictive concept, the effective reduced electric field (EREF), that only assumes that v is constant. In this concept the effective electric field is reduced according to

$$\left(\frac{E}{N} \right)_e = \frac{E}{N} \cos \theta = \frac{E}{N} \frac{\left(\frac{v}{N} \right)}{\left[\left(\frac{v}{N} \right)^2 + \left(\frac{\omega}{N} \right)^2 \right]^{\frac{1}{2}}}, \quad (2)$$

where $\omega = eB/m$ is the cyclotron frequency. θ can be visualized as the angle the electron avalanche or streamer is tilted with respect to the electric field and is defined as

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$$\theta = \cos^{-1} \left[\left\{ 1 + \left(\frac{e}{m} \frac{1}{v_o} \frac{B}{N} \right)^2 \right\} \right]^{-\frac{1}{2}} = \tan^{-1} \left[\frac{e}{m} \left(\frac{N}{v} \right) \frac{B}{N} \right]. \quad (3)$$

There is an obvious similarity between Eq. (1) and (2), but the EREF concept has a better theoretical basis and less restrictive assumptions so it is applicable over a larger variation in parameters.

EREF assumptions include the secondary ionization coefficient remaining constant with increasing magnetic field due to the heavy mass of the positive ions. Raju [2] cautions about accepting that assumption and provides data showing that the assumption fails for E/N values greater than $180 \times 10^{-21} \text{ Vm}^2$ ($E = 52 \text{ kV/cm}$ at one atmosphere) in the case of H_2 . This affects the formative time lag for breakdown. The only data available on formative time lag is for O_2 , N_2 , and dry air at low pressure and magnetic field [4]. Also, the EREF concept is based on a uniform electric field and neither electronegative gases nor negative ions are considered.

The EREF and equivalent pressure concept have been shown to agree with data at low gas pressures. Data [5] for higher gas pressures, between 7 and 22 torr, and for magnetic fields $\leq 1.2 \text{ T}$ remain in reasonable agreement with the EREF concept. However, the scaling of this data to higher fields at atmospheric pressure diverges from the EREF concept. Monte Carlo simulations [6] at higher fields and pressures also vary from the EREF concept.

II. Experiment Design

The experiment was designed around the capabilities of existing equipment in the High Voltage Laboratory. Three items were particularly important; a high current pulsed generator referred to as the RPX Bank, a coaxial load used for hydrodynamic experiments at high magnetic pressure, and a variable pulse width, 100-kV capacitive discharge unit (CDU). The RPX Bank and load are described in Ref. [7], and details of the CDU can be found in Ref. [8]. The laboratory is well equipped with a variety of high-voltage, high-current, and video diagnostics. For this paper the design is divided into Physics, Electrical, Mechanical, and Diagnostics sections. An illustration of the coaxial load as modified for this experiment is shown in Fig. 1 as a reference for the following discussion.

A. Physics Design

A primary consideration is the minimum magnetic field required to demonstrate an increase in the electrical field stress required for breakdown. We anticipated that fields above 15 Tesla would be sufficient based on the EREF concept. For our coaxial geometry the magnetic field can be expressed

$$B(\text{T}) = \frac{20 I(\text{MA})}{r(\text{cm})}, \quad (5)$$

where r is the radial distance from the axis and I is the applied current. The RPX Bank is nominally operated at 750 kA. Operations at higher currents, 1 MA, are possible but require replacing connectors/cabling and accepting shortened capacitor life times. With these considerations, an inner conductor radius of $\leq 1 \text{ cm}$ was chosen.

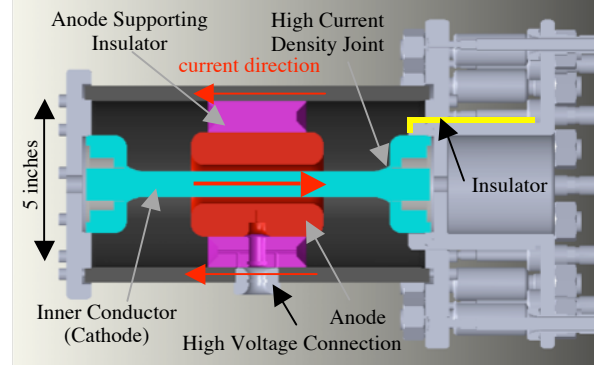


Figure 1. Illustration of the coaxial load shown with a 2 cm diameter inner conductor and anode.

The next consideration was the generation of the electrical field. At one atmosphere in SF_6 in a uniform field, the field for breakdown, E_b , is $\sim 90 \text{ kV/cm}$ [9,10]. A value twice E_b , was desirable as an initial design point. For a coaxial geometry, the quasi-static electric field can be expressed as

$$E = \frac{V}{r \ln \left(\frac{r_a}{r_c} \right)} \quad (6)$$

where r_a is the inner radius of the anode (outer conductor), r_c is the outer radius of the cathode (inner conductor), and V is the potential difference.

Producing the field inductively was not practical. We elected to drive the anode with a second, high-voltage, pulse generator. Separate pulse generators for the current (magnetic field) and voltage (electrical field) provided more control on the experiment.

Mechanical and electrical considerations (see sections below) led to a cylindrical anode placed inside the load and around the inner conductor as shown in Fig. 1. A choice of 1.5 cm for the anode inner radius with a 0.5 cm radius cathode and 100 kV applied potential yields:

$$E_{\text{cathode}} = 182 \text{ kV/cm} \quad E_{\text{anode}} = 60.7 \text{ kV/cm}$$

Preliminary high voltage testing of the load found that breakdown occurred when an applied potential of 70 kV, or an electrical field stress of 127 kV/cm on the cathode, was reached. By removing the inner conductor, it was determined that the high voltage feed through at the outer wall would breakdown between 90-95 kV. To allow a greater margin between gap and feed through breakdowns, the diameter of the inner conductor was increased to 2 cm. With a 1.5 cm radius anode, 1.0 cm radius cathode, 1 MA current, and 90 kV potential:

$$\begin{aligned} E_{\text{cathode}} &= 222 \text{ kV/cm} & E_{\text{anode}} &= 148 \text{ kV/cm} \\ B_{\text{cathode}} &= 20 \text{ T} & B_{\text{anode}} &= 13.3 \text{ T} \end{aligned}$$

The new expected gap breakdown potential was 51 kV.

Cathode material and surface preparation were considered to enhance the probability of breakdown in the gap. Published test results [11] for materials of interest (copper, aluminum, stainless steel) did not indicate significant electrode material or surface roughness impact for SF₆ at one atmosphere. All our cathodes were fabricated with a 32 micro-inch finish, except for a 1-cm diameter cathode with half the surface roughened with 80 grit sandpaper. Due to the amount of surface area, UV illumination was not considered necessary to ensure breakdown [12,13].

Both the electric and magnetic fields are non-uniform for the coaxial geometry. A figure of merit for the amount of electric field non-uniformity is the form factor:

$$\text{Form Factor} = \frac{E_{\text{peak}}}{E_{\text{average}}} = \frac{r_a - r_c}{r_c \ln\left(\frac{r_a}{r_c}\right)} \quad (7)$$

The peak field is the highest electric field between the electrodes and the average field is the potential divided by the electrode spacing. The issue with a high form factor is that an avalanche (streamer) may initiate in a high electric field region then dissipate in a weaker field before completing a breakdown. Similarly, an avalanche may be suppressed in regions of high magnetic field but initiate part way across the gap forming a streamer that eventually crosses the entire gap. For a coaxial geometry,

$$\frac{E}{B} = \frac{2\pi V}{\mu \ln\left(\frac{r_a}{r_c}\right) I} \quad (8)$$

is independent of radial position between the electrodes. For a r_a of 1.5 cm and r_c of 1.0 cm, the form factor is only 1.2. Due to our low form factor and constant E/B ratio, the non-uniform fields were not considered an issue.

B. Electrical Design

A major challenge for the electrical design was proper integration of the two pulsed generators. An accurate circuit model required estimates of the inductance, resistance, and capacitance of the circuit and the first step in producing these estimates was the anode design.

There were two design criteria for the anode. First was that the electric field between the anode and cathode to be constant longitudinally over at least three times the gap spacing. This distance was desired to ensure that avalanches originating from the cathode would not miss the anode due to their angular tilt with respect to the electric field at high magnetic fields. For an average magnetic field of 20 T, θ is about 30°. For the tested configuration, this longitudinal distance of constant field was about 15 times the gap spacing. The second criteria was that the electrical field on the anode away from the cathode should be less than 90 kV/cm for an anode to cathode potential of 100 kV to avoid the possibility of an avalanche forming between the anode and other surfaces within the load, e.g. the outer conductor/wall.

Once a general mechanical drawing of the coaxial load with anode was established, various simulations were performed to determine the inductance, resistance, and capacitance. Initial values calculated were 110 nH, 178 mΩ, and 12 pF, respectively. Resistance is the most challenging calculation as the appropriate skin depth, i.e. frequency components of the current, is required as well as some assumptions on contact resistance between the various joints. All values were measured after the experiment was assembled and used to determine the correct charging of the RPX Bank and triggering of the HV pulse generator.

Under normal operating conditions of the RPX bank, the load floats and the bank is grounded. With the introduction of the HV pulse generator to the circuit, it was important to create a low impedance ground connection from the RPX bank to the HV pulse generator to keep both at the same reference potential. Co-location and the use of a flat, wide, copper strip provided such a connection.

The operation of both the high-current and high-voltage sources required an electrical connection at the load, but each needed to operate independently. In simple terms, the RPX bank should not see the 100 kV HV pulse generator in the circuit during operation and the 100 kV HV pulse generator should not mind that 1 MA is flowing through the cathode. After careful circuit modeling, it was determined this could be accomplished with cable impedance. The high current would not flow through the 60 Ω high-voltage pulse generator cable and the high voltage on the isolated anode is not transferred to the RPX bank.

The electrical issue for the anode support insulator was surface flashover. Published data [14] indicates the electric field at the contact between the insulator and electrode should be much lower 50 kV/cm. The insulator was designed with a concave, or inverted V, surface to achieve this condition. The final design had a maximum electric field at the contact points of 10 kV/cm. Several materials were considered for the insulator. High-density polyethylene (HDPE) was selected for the initial high voltage testing because of mechanical concerns regarding brittleness and possible cracking/chipping during the high current pulses, and proved to adequately resist flashover.

The high-voltage feed through design was problematic. The cable insulation was sufficient to avoid bulk breakdown. However, localized enhanced fields occurred where the cable insulation passed through the cable bushing as shown in Fig. 2. A concern was that this high field would lead to plasma formation. The plasma could move/track inward along the cable insulator inside the anode support insulator causing arcing between the anode and outer cylinder. To avoid this mechanism for arcing, an O-ring was incorporated into the anode support insulator to create a tight seal around the HV cable. A series of holes was also bored into the anode support insulator to ensure that SF₆ filled the various voids.

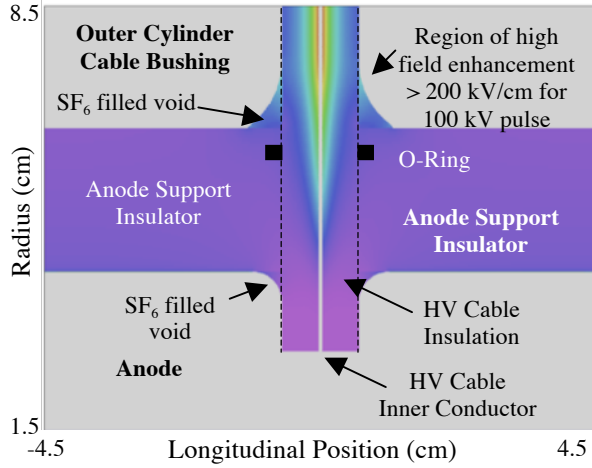


Figure 2. 3-D electrostatic simulation slice view bisecting the HV cable and feed through. Color coding represents electric field magnitude. Red is high and violet is low.

C. Mechanical Considerations

The most difficult mechanical considerations were related to magnetic pressure and current connections. Magnetic pressure can be expressed as

$$P = \frac{B^2}{2\mu} = \frac{\mu I^2}{8\pi^2 r^2}, \quad (9)$$

The greatest pressure would be on the inner conductor (cathode). For a 1-MA current pulse and a 1.0 cm radius cathode, the pressure would be 2.31×10^4 psi. Although this is a large pressure, the yield stress in compression is ~30% greater than the ultimate tensile strength in aluminum and its alloys [15]. The ultimate tensile strength of AL 6061-T6 is about 3.8×10^4 psi and an estimate for the yield stress in compression is 5.0×10^4 psi.

Of greater concern is the hoop stress, σ_h , in the anode. The Lamé Equations are appropriate for our anode geometry. Due to the $1/r^2$ variation of the magnetic pressure, the hoop stress in our case is simply the pressure,

$$\sigma_h = P. \quad (10)$$

For a 1.5 cm r_a and 1-MA current, the inner hoop stress is 1.54×10^4 psi. Applying a SF of 3 on yield (Static) leads to a desired material tensile strength of at least 4.6×10^4 psi. Several materials were considered and AL 7075-T6 was chosen for the anode as it possessed sufficient strength ($\sigma_s = 6.7 \times 10^4$ psi) and is easily machined. The hoop stress on the outer conductor of the load is about 2.9×10^3 psi. AL 6061-T6 was used for the outer conductor.

The end flanges on the coaxial load are also subjected to large forces. Integrating the pressure over the surface of the flange:

$$F = \int_{r_i}^{r_o} \left(\frac{\mu I^2}{8\pi^2 r^2} \right) 2\pi r dr = 10^{-7} I^2 \ln \left(\frac{r_o}{r_i} \right), \quad (11)$$

where $r_i = r_c$ is the smallest radius that the current flows along and r_o is the largest. Determining r_o is not straightforward. On the shorted end of the load (right end

in Fig. 1) the current runs out to the inner radius of the outer conductor, 6.35 cm. On the drive end of the load, the flange is not continuous with a break at the indicated insulator to allow for the current to enter/exit the load. Following the current path, the actual radial distance the current flows is to the radius of the 12 cable feeds, about 10.8 cm. This load is supported by 12 Torlon® rods that provide electrical isolation. A worse case scenario with one MA current and a 0.5 cm r_c produces a tensile stress on the bolts of 13,442 psi. The ultimate tensile strength for Torlon® is 18,000 psi or a SF of only 1.3.

The above calculations assumed static forces and pressures. Since the current/magnetic pressure is applied in a pulse over about 70 μ s reaching a peak in 30 μ s, dynamic containment should be considered. A quick check is to see if the pressure pulse is short compared to the oscillating period of a thin cylindrical container [16]:

$$T_M = 2\pi r_m \sqrt{\frac{\rho}{Y}}, \quad \text{where} \quad (12)$$

r_m is the mean wall radius, ρ is the density and Y is Young's modulus of the wall material. Using nominal values of 2.7×10^3 kg/m³ and 6.9×10^{10} N/m² for aluminum, T_M is about 30 μ s to 60 μ s for our load. Thus our pulse is too slow to gain significant dynamic containment and the static model is appropriately conservative.

Forces on the HV cable and asymmetric forces on the anode during breakdown were estimated. Displacement current through the cable during the application of the high voltage is not significant, but during a breakdown as much as 400 A could be drawn. For a 1 MA high current experiment, a longitudinal force of 37 N would be imposed on the cable for the duration of the arc. The anode could also experience unbalanced forces of 79 N longitudinally and 1.5 N radially during the arc.

The concentricity of the anode with respect to the inner conductor was a general tolerance issue. Lack of concentricity causes an imbalance of forces on the anode that would tend to center the anode about the cathode. We estimated that the anode would experience approximately 1,000 lbf of centering force per mil that the anode was off center with respect to the cathode. The concentricity of the anode was determined by the accuracy of the support insulator within the outer cylinder and the concentricity of the cathode through the end flanges to the outer cylindrical. We estimate that the total tolerance build up led to an anode concentricity error of 0.5 mils in radius. The error also leads to an azimuthal variation in the electric field of less than $\pm 0.25\%$.

The high voltage experiments were done with the coaxial load filled with SF₆ at nominally one atmosphere absolute pressure. To ensure that voids were filled, a mechanical pump was used to establish a vacuum in the load before SF₆ was introduced through a port in the bottom of the load. The SF₆ was allowed to flow through a port at the top of the load to an exhaust hood. The HV feed through was located on the side (90 degrees from the SF₆ ports) to avoid trapped air.

The current joint design between the inner conductor/cathode and end flanges went through several iterations. Based on published data [17] the joint contact pressure should be greater than about 3,500 psi to realize minimum contact resistance. The contact surface should extend to at least 3 skin depths, or about 2.7 mm in aluminum for our pulse rise time. After the first high current experiment it was necessary to revisit the design resulting in a sophisticated flared design that permitted a higher contact pressure and used the magnetic pressure to improve contact during the high current pulse.

D. Diagnostics

The anode voltage was monitored by a geometrically designed, aqueous NaCl, divider probe commonly referred to as a voltage resistive divider (VRD). Features of these probes include a fairly fast rise time (~ 5 ns), an ability to handle high voltage transient pulses, and a matched impedance of 50 ohms.

The primary current measurements were taken with Rogowski coils located at the output of each of the three modules of the RPX Bank and summed for the total current. A Faraday rotation diagnostic that measured the total load current was also used. The Rogowski coils and the Faraday rotation diagnostic agreed to within $\pm 4\%$ and this variation was used for the uncertainty in the magnetic field values shown in Fig. 5.

A large format camera was used to determine gap versus feed through arcs. The normal procedure was to take a "double exposure", the first with a lighted background exposure and the second with the lights turned off with the camera shutter open during the experiment to permit the orientation of the arc with respect to the hardware components to be determined.

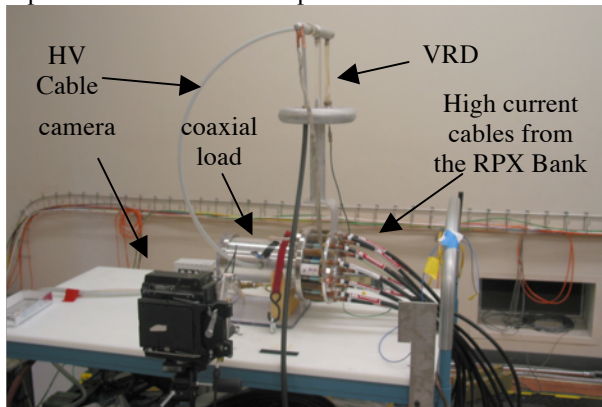


Figure 3. Photograph of experiment shows the coaxial load, VRD, voltage/current cables, and camera.

III. Measurements

The testing was performed in two stages. Initial tests only involved the HV pulse generator and the load with temporary end flanges. These tests were to check the performance of the HV pulse generator, the HV feed through connection, and verify the location of the

breakdown. The second stage involved attaching the RPX Bank to the fully assembled load and HV pulse generator.

A. No Magnetic Field

The flange used on the drive end of the coaxial load was replaced with Lexan® to permit the interior to be viewed and photographed. A double exposure photograph using an open shutter in a dark room during application of the high voltage to image the arc followed by a normal picture with lights on after the pulse to show hardware was used to determine the arc position. A total of nine pulses resulting in breakdown between the anode/cathode were taken. Interestingly, all nine arcs occurred on the smooth side of the cathode rather than the roughened side.

We determined that for the 1-cm diameter cathode the breakdown potential was ~ 70 kV with a maximum electrical field stress of 127 kV/cm on the cathode. For a 2-cm diameter cathode, the breakdown potential was reduced to ~ 43 kV or a electric field stress of 104 kV/cm. The change in the electrical field at breakdown may be related to the lower form factor of the new configuration.

After these tests, the cathode (inner conductor) was removed to determine the next location of breakdown. Around 95 kV a breakdown/flashover would occur along the high voltage feed. The light from this arc was visible through the insulator around the cable and through the cable itself looking at the exterior penetration.

B. Magnetic Insulation

The next stage involved both high current and high voltage. The current at the time of the high voltage pulse could be determined by a noise signal that served as a timing fiducial superimposed on the current signal.

Determining the improvement in the breakdown potential/electric field was accomplished by performing comparison HV-only experiments immediately before and after the combined high voltage/current experiment. Fig. 4 shows the anode potential as a function of time for Shot 6b, the 1-MA experiment, and three following experiments with HV only for comparison. The HV only experiments were very consistent.

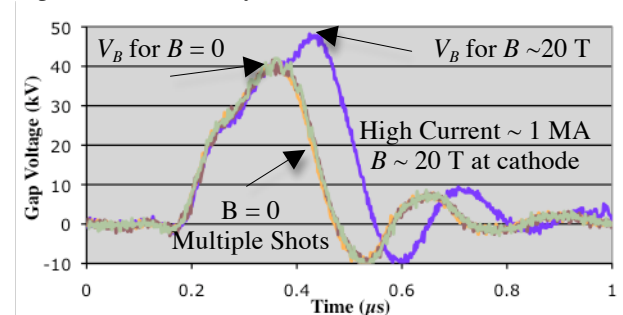


Figure 4. Anode potential for the 1 MA experiment showed an 18% improvement in V_B .

A difficulty with the lower current/magnetic field experiments was separating the small increase in

breakdown potential from a ~ 300 MHz oscillation on the signal. For the purposes of this report, a 10 ns averaging window approximately centered about the peak for each signal, essentially a 100 MHz filter, was used to establish a peak potential. The vertical error bars shown in Fig. 5 were established by the standard deviation of these averaged values.

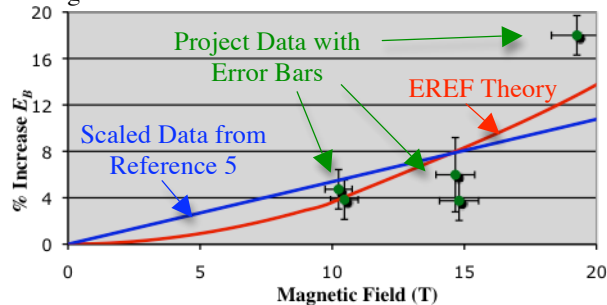


Figure 5. Experimental measurements plotted against EREF Theory and scaled data from Reference 5.

IV. Summary

The project achieved the primary goal of demonstrating magnetic insulation in SF_6 at atmospheric pressure. The measurement at ~ 20 Tesla was unambiguous and all data were in reasonable agreement with the EREF Theory. The data did show a greater than linear increase with pressure represented by the simple extrapolation of low-pressure data. The increase in breakdown field strength from ~ 15 T to ~ 20 T is very promising for very high current coaxial flux compression generators. A total of six high-current pulses from 500 kA to 1 MA were applied to the load with five of these combined with high voltage pulses to the anode.

Two interesting observations were made during the course of the project. First was the arcing from the smooth surface of the 1-cm diameter cathode that had one side roughened with 80 grit sandpaper. All breakdowns that occurred with this cathode were identified with marks on the smooth surface. A highly polished surface may not be desirable.

The next observation involved the importance of form factor on breakdown. The two form factors, 1.8 and 1.2, used in the initial testing of the high voltage pulse generator had different electric fields for breakdown, 127 kV/cm and 104 kV/cm respectively. Published data varied on the importance of the form factor, but all considered form factors of 1.8 or less as small, i.e. relatively uniform.

V. Acknowledgements

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